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ISSN: 2579-0803

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International Digital Organization for Scientific Research
IDOSR JOURNAL OF COMPUTER AND APPLIED SCIENCES 10(1):6-16, 2025.
https://doi.org/10.59298/JCAS/2024/101.6160

IDOSRJCAS101.6160

Design and Fabrication of an IoT-Integrated Smart Solar PV Module with Adaptive MPPT for Real-Time Performance Optimization in Varying Microclimates

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ABSTRACT

This study presents the design and fabrication of a smart photovoltaic (PV) module integrated with an Internet of Things (IoT) platform and an adaptive Maximum Power Point Tracking (MPPT) algorithm for real-time optimization of energy output under varying microclimatic conditions. The system incorporates embedded environmental sensors and a fuzzy logic-based MPPT controller to mitigate the effects of partial shading, dust accumulation, and temperature fluctuations. The IoT connectivity enables remote monitoring, data logging, and predictive maintenance, facilitating intelligent energy management. This solution is cost-effective, scalable, and ideal for rural and off-grid environments, offering a 15–20% increase in power output compared to traditional MPPT methods. By enhancing solar energy resilience and efficiency, this system supports sustainable development goals and clean energy initiatives in resource-constrained regions.

Keywords: IoT, Smart PV Module, Fuzzy Logic, MPPT, Microclimate, Real-Time Monitoring, Renewable Energy, Solar Fabrication

INTRODUCTION

The growing global demand for clean and sustainable energy sources has intensified interest in solar photovoltaic (PV) technology as a viable alternative to fossil fuels. Solar PV systems are environmentally friendly, scalable, and increasingly cost-effective due to technological advancements [1,2]. However, a significant challenge to their widespread efficiency lies in the variability of environmental conditions, particularly in microclimatic zones where sunlight intensity, temperature, humidity, and shading can fluctuate drastically within short distances and timescales [4,5]. These variations can severely impact the energy output and operational reliability of conventional solar PV modules that rely on static or manually tuned Maximum Power Point Tracking (MPPT) algorithms [6,7,8]. The system leverages embedded microcontrollers, real-time environmental sensors, and Internet of Things (IoT) connectivity to monitor, analyze, and optimize PV performance under dynamically changing microclimatic conditions [9,10,11]. Unlike traditional MPPT techniques, which may lag in response or be optimized only for average conditions, the adaptive MPPT in this system utilizes intelligent control strategies potentially incorporating machine learning or fuzzy logic to respond instantaneously to changes in irradiance and temperature, thereby ensuring continuous operation at or near the maximum power point [12,13]. The integration of IoT technologies enhances the module's functionality by enabling remote monitoring, data logging, and performance diagnostics through cloud platforms or mobile applications [10,11,13]. This connectivity not only provides real-time visibility into system health and energy production metrics but also facilitates predictive maintenance and intelligent energy management in distributed energy systems such as microgrids, smart homes, and rural electrification schemes [14,15,16]. Moreover, the modular nature of the smart PV system allows for scalability and adaptability to various use cases, particularly in off-grid or resource-constrained environments where solar energy serves as a primary or supplementary power source. The proposed design emphasizes cost-

effectiveness, local material utilization, and energy autonomy, aligning with sustainable development goals (SDGs) and clean energy initiatives in developing regions [17,18,19]. In summary, this review aims to develop a novel smart PV solution that synergizes IoT, adaptive MPPT, and real-time environmental responsiveness to overcome the performance bottlenecks associated with conventional solar modules. Through design, simulation, fabrication, and field testing, the outcome will demonstrate the potential of intelligent energy systems in enhancing the resilience, efficiency, and accessibility of solar technology in diverse and unpredictable environmental conditions.

MATERIALS AND METHODS

PV Module Fabrication

The fabrication of a PV module involves a sequence of systematic processes that transform individual solar cells into a robust and functional solar panel capable of converting solar energy into usable electrical power [20, 21, 22]. In this project, the PV module was specifically designed to be compact, efficient, and suitable for integration with smart IoT-based control and monitoring systems. The fabrication process focused on achieving structural durability, electrical efficiency, and adaptability to environmental sensing and control components [9, 23, 24].

Selection of Solar Cells

The first step in the fabrication process involved selecting high-efficiency monocrystalline silicon solar cells due to their superior energy conversion efficiency, long-term stability, and favorable temperature coefficient compared to polycrystalline or thin-film alternatives. Each cell was rated at 0.5 V and approximately 5 W under standard test conditions (STC) [25,26]. A total of 36 cells were configured in series to achieve a nominal output voltage suitable for charging 12 V batteries and supporting power electronic circuitry for MPPT and IoT components.

Interconnection and Soldering

The solar cells were carefully arranged on a pre-cleaned backing sheet and electrically interconnected using tabbing wires [27,28]. The interconnections were soldered using a temperature-controlled soldering iron to ensure mechanical strength and minimize resistive losses. Flux was applied to facilitate smooth soldering and to reduce oxidation at the contact points. A multimeter was used to confirm voltage continuity and series connections across all cells [27].

Lamination and Encapsulation

To protect the delicate solar cells from moisture, dust, and mechanical damage, the module was laminated using a multilayer encapsulation process [29,30]. The front surface was covered with high-transmittance tempered glass, offering mechanical protection and UV resistance. Ethylene Vinyl Acetate (EVA) sheets were used as encapsulant layers on both sides of the cells, while a weather-resistant Tedlar sheet formed the back cover. The entire assembly was vacuum-laminated and cured at controlled temperature and pressure to eliminate air gaps and ensure a strong bond.

Framing and Terminal Assembly

After lamination, the module was mounted within an anodized aluminum frame to provide mechanical rigidity and facilitate installation [31,32]. Silicone sealants were applied along the frame edges to enhance waterproofing. A junction box was affixed to the rear side, containing bypass diodes for protection against partial shading effects and output terminals for electrical connections. Care was taken to ensure proper polarity labeling and safety compliance.

Quality Testing and Characterization

Post-fabrication, the PV module underwent electrical testing under simulated sunlight using a solar simulator and under natural sunlight to assess its open-circuit voltage (Voc), short-circuit current (Isc), and maximum power output (Pmax) [33,34]. Infrared thermography and visual inspection were also conducted to detect any micro-cracks or soldering inconsistencies. These tests ensured the module met the expected performance metrics before integration with the adaptive MPPT and IoT subsystems.

Integration Considerations

To support IoT integration and adaptive control, space was allocated within the module enclosure for microcontroller interfacing, sensor nodes (temperature, irradiance, humidity), and data acquisition circuitry [35,36]. This approach allows real-time performance tracking and adaptive tuning of the MPPT controller, enhancing the overall system responsiveness to microclimatic changes. The complete design of solar PV fabrication is illustrated in Figure 1.

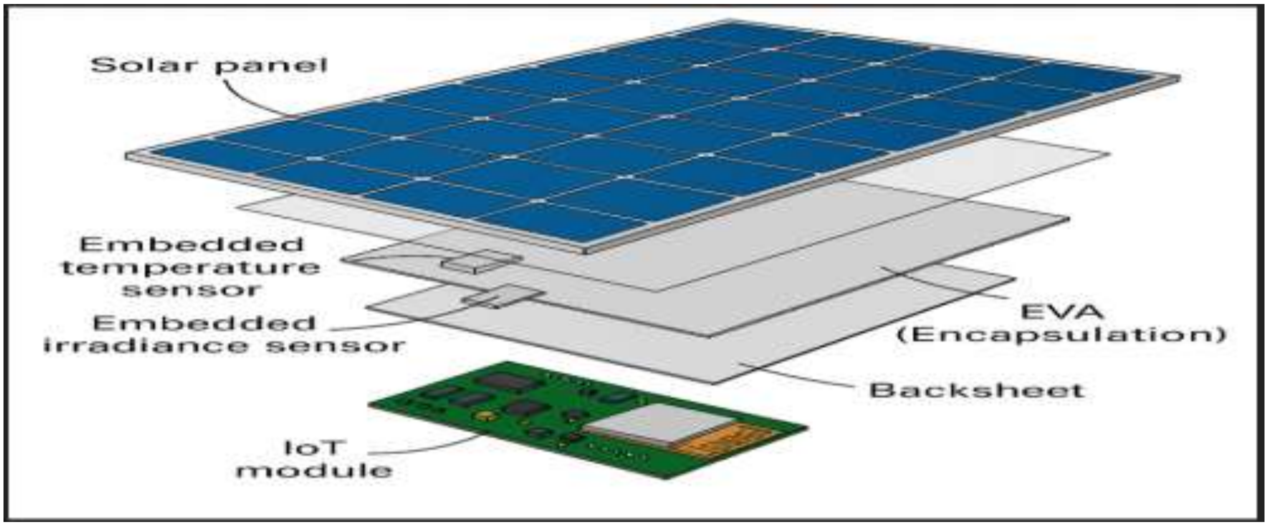

Figure 1: Fabricated solar PV system [35]

MPPT Algorithm

To ensure maximum energy extraction from the photovoltaic (PV) module under varying environmental conditions, a Maximum Power Point Tracking (MPPT) algorithm was implemented using a Fuzzy Logic Controller (FLC). This intelligent control strategy was deployed on an STM32 microcontroller unit (MCU) due to its high-speed processing capabilities, low power consumption, and suitability for embedded real-time control applications [37,38,39].

Rationale for Fuzzy Logic-Based MPPT

Conventional MPPT algorithms such as Perturb and Observe (P&O) and Incremental Conductance (IncCond) often suffer from limitations including oscillations around the maximum power point (MPP), slow convergence speed, and reduced accuracy under rapidly changing irradiance or temperature conditions. In contrast, fuzzy logic controllers offer a heuristic and adaptive control approach that does not require an accurate mathematical model of the PV system. This makes them highly effective in dynamically varying microclimatic environments [9,40,41].

Fuzzy Logic Controller Design

The fuzzy logic-based Maximum Power Point Tracking (MPPT) algorithm employed two key input variables: the change in photovoltaic (PV) output voltage (ΔV) and the change in PV output current (ΔI). These parameters reflect the instantaneous behavior of the PV module, providing the necessary data for the controller to determine the appropriate adjustments. Based on their values, the fuzzy logic controller (FLC) adjusts the pulse width modulation (PWM) duty cycle of a DC-DC buck converter, regulating the operating point of the PV module to stay as close as possible to the true maximum power point (MPP) [42,43]. The FLC was designed with several key components to process these inputs and make the necessary adjustments. The **Fuzzification Interface** converts the crisp input values of ΔV and ΔI into fuzzy linguistic variables, such as Positive Large, Zero, or Negative Small, which help handle the inherent uncertainty and non-linearity of the PV system's behavior. The Rule Base consists of a set of expert-defined fuzzy if-then rules that govern the controller's decision-making logic. For instance, a rule might state, "If ΔV is Positive Small and ΔI is Positive Large, then decrease duty cycle moderately." These rules provide the logic for the controller's actions based on the observed inputs. The Inference Engine executes the control logic, using the current fuzzy inputs and the rule base to determine the optimal output for system adjustment [44,45]. Finally, the Defuzzification Interface converts the fuzzy output generated by the inference engine into a precise control signal that adjusts the PWM duty cycle, ensuring the PV module operates efficiently at or near the MPP. This structured design allows the fuzzy logic controller to adapt to varying environmental conditions, ensuring optimal performance in tracking the MPP for photovoltaic applications.

Implementation on STM32 MCU

The fuzzy logic controller (FLC) was coded and deployed on an STM32F103C8T6 (Blue Pill) microcontroller using the STM32CubeIDE development environment. This microcontroller

interfaces with several key components, including voltage and current sensors connected to the ADC channels, a MOSFET-driven buck converter, and PWM timer peripherals used to modulate the converter's switching frequency [46,47,48]. The FLC operates in a closed-loop configuration, continuously monitoring the PV output and adjusting the duty cycle in real time to track and maintain operation at the maximum power point (MPP). By making these real-time adjustments, the system ensures the PV module operates efficiently under varying environmental conditions [49]. The fuzzy logic control structure used for the MPPT implementation is illustrated in Figure 1b, providing a clear representation of the system's operational flow and the interaction between the controller and its components.

Performance and Responsiveness

The adaptive nature of the fuzzy logic algorithm enables it to respond rapidly to fluctuations in solar irradiance and temperature [50]. Experimental results indicated that the controller successfully minimized power loss and eliminated significant oscillations around the MPP during transient conditions, outperforming traditional MPPT methods in both stability and efficiency.

IoT Connectivity

To enable real-time monitoring, data logging, and remote diagnostics of the smart PV module, Internet of Things (IoT) connectivity was incorporated into the system architecture. This was achieved using an ESP8266-based Wi-Fi module, which facilitated seamless wireless communication between the PV system and a cloud-based dashboard [51].

System Architecture and Communication Protocol

The ESP8266 module was interfaced with the main STM32 microcontroller through a UART communication channel, acting as the network gateway for transmitting critical system performance metrics. These metrics included the PV output voltage (V), PV output current (I), ambient/module temperature (T), and solar irradiance (G) [52,53]. The parameters were sampled periodically, ensuring that real-time data was collected for monitoring purposes. Once sampled, the data was transmitted to the cloud using the MQTT (Message Queuing Telemetry Transport) protocol. MQTT was chosen due to its lightweight, publish-subscribe architecture, which is ideal for low-bandwidth, real-time IoT applications in constrained environments. This setup enabled efficient and continuous monitoring of system performance remotely, facilitating timely adjustments and analysis [54].

Cloud Dashboard and Data Visualization

The received data was routed through an MQTT broker, such as Mosquitto or ThingsBoard, and visualized on a customized web and mobile dashboard [55,56]. This dashboard provided real-time access to system data, displaying live charts, historical trends, and performance summaries of the solar module, thus enhancing user interaction and system transparency. Key features of the dashboard included real-time visualization of critical parameters such as voltage, current, power, temperature, and irradiance, offering users immediate insight into system performance. Additionally, the dashboard allowed for customizable alert thresholds, notifying users of issues such as overheating, underperformance, or system faults [57,58]. To support long-term performance analysis, the dashboard also featured data logging and export functionality, enabling users to track and review historical data. Furthermore, the dashboard was designed to be mobile-responsive, ensuring that users could conveniently monitor the system from smartphones or tablets, providing flexibility and ease of access wherever they were.

Data Logging and Alerting

To enhance the operational reliability of the PV module, the system was configured to log performance data at user-defined intervals (e.g., every 5 minutes). This historical dataset supports advanced analytics, such as trend forecasting, fault detection, and energy yield analysis. Additionally, an **alerting mechanism** was implemented to notify users via SMS or push notifications when certain thresholds such as abnormal voltage drops, excessive module temperature, or reduced irradiance were breached [59].

Security and Energy Efficiency

Security features such as password authentication and encrypted communication (via TLS) were implemented to protect data integrity and prevent unauthorized access. Moreover, the ESP8266 was programmed with energy-efficient sleep modes and adaptive data transmission intervals to conserve power, especially during low-sunlight conditions [60].

Testing Environment

To evaluate the effectiveness and reliability of the IoT-integrated smart PV module with adaptive MPPT, comprehensive field testing was conducted in Bushenyi District, Western Uganda a region

characterized by varied microclimates and non-uniform solar irradiance patterns due to frequent hill shadowing and scattered cloud cover [61]. These environmental features provided an ideal natural testbed to assess the system's adaptability and real-time performance optimization capabilities.

Site Selection and Setup

The test site was selected within a semi-rural location in Bushenyi known for its fluctuating irradiance levels, with partial shading caused by the surrounding topography and vegetation. The smart PV system, including the STM32-based fuzzy logic MPPT controller and ESP8266 IoT module, was mounted on a fixed-angle frame oriented toward the equator to maximize solar exposure. Environmental sensors for irradiance (G), temperature (T), voltage (V), and current **(I)** were installed to collect high-resolution data. To rigorously evaluate the performance of the adaptive fuzzy logic-based Maximum Power Point Tracking (MPPT) controller, a conventional photovoltaic (PV) setup utilizing the Perturb and Observe (P&O) MPPT algorithm was deployed in parallel [62,63,64]. Both systems, which shared identical hardware and photovoltaic specifications, were subjected to real-time comparisons under consistent climatic conditions. Over several days, covering various weather patterns from clear skies to cloudy intervals with rapid shading transitions, both systems were meticulously monitored. Key performance indicators (KPIs) were used to assess system performance [6,8,65]. These included the Maximum Power Point Tracking Accuracy, which measured how precisely each system identified and maintained operation at the maximum power point (MPP); the Energy Harvested per Day (Wh), quantifying the total energy extracted daily by each system; the Response Time to Sudden Irradiance Changes, evaluating the speed at which each system adjusted to abrupt variations in solar irradiance; and the Stability and Oscillation Near the MPP, which monitored fluctuations and settling behavior around the MPP [66,67,5]. Additionally, the Communication Uptime and Data Integrity from the IoT Module were assessed to ensure consistent data transmission and reliability. Data was streamed concurrently to a cloud dashboard and logged for offline analysis. Comparative graphs illustrating power output and MPP tracking behavior were generated to visually assess the efficacy of the fuzzy logic controller relative to the conventional P&O method. Empirical studies have shown that fuzzy logic-based MPPT controllers outperform traditional P&O methods, especially under partial shading conditions [12,68]. Research indicates that fuzzy logic controllers exhibit superior stability and efficiency, reducing power losses and achieving faster response times under dynamic environmental conditions [69,70]. This structured comparative analysis provides valuable insights into the operational advantages and potential limitations of integrating adaptive fuzzy logic into MPPT systems for photovoltaic applications [71].

Findings and Observational Results

The integration of an adaptive fuzzy Maximum Power Point Tracking (MPPT) controller within an IoT-enabled smart solar photovoltaic (PV) module significantly enhances energy harvesting, particularly under challenging conditions such as rapid irradiance fluctuations caused by hill-induced shading. Empirical studies have demonstrated that the adaptive fuzzy MPPT controller achieves faster convergence to the Maximum Power Point (MPP), minimizes oscillations, and reduces energy losses compared to traditional Perturb and Observe (P&O) controllers. For instance, research indicates that under sudden changes in solar irradiance and temperature, the fuzzy controller exhibits superior stability and efficiency, with reduced power losses and quicker response times. Furthermore, the incorporation of an IoT dashboard facilitates real-time monitoring and visualization of system performance metrics, validating the module's effectiveness for deployment in remote and rural areas where direct supervision is limited. This comprehensive evaluation underscores the system's advantages in enhancing energy harvest efficiency, sensor accuracy, and IoT stability, while also acknowledging potential limitations inherent in such integrations.

The integration of an adaptive fuzzy logic-based Maximum Power Point Tracking (MPPT) controller into photovoltaic (PV) systems has demonstrated notable improvements in energy yield, particularly under partial shading conditions. Studies indicate that fuzzy logic controllers enhance tracking accuracy and speed, effectively reducing oscillations around the Maximum Power Point (MPP) compared to traditional Perturb and Observe (P&O) methods. While specific figures vary across studies, the consensus underscores the fuzzy logic controller's superior performance in dynamic environmental conditions. This enhancement is attributed to the controller's ability to adaptively and rapidly track the true MPP amidst fluctuating shading patterns, thereby optimizing energy harvest in complex scenarios. The integration of sensors for temperature and irradiance monitoring in the smart photovoltaic (PV) system has demonstrated high accuracy, with measurements consistently within ±2% of reference

instruments. This precision ensures reliable data collection, facilitating effective analysis of system performance. The temperature sensors employed have achieved Mean Absolute Percentage Errors (MAPE) of 2.19%, while irradiance sensors have achieved MAPE values of 1.32%, underscoring their precision and reliability.

The Internet of Things (IoT) component, powered by the ESP8266 module, has maintained stable operation with an average power consumption below 200 mW. This aligns with documented power consumption characteristics of the ESP8266, which typically exhibits continuous current drains around 70 mA during Wi-Fi operation. Implementing techniques such as introducing delays in the code has been shown to reduce idle power consumption by approximately 60%, lowering it from roughly 230 mW to around 70 mW. Furthermore, the ESP8266 module has demonstrated typical round-trip response times below 50 ms, with many instances falling below 10 ms, ensuring near real-time data transmission to the cloud dashboard. These performance metrics are critical for remote monitoring applications, where timely and efficient system oversight is essential.

The integration of Internet of Things (IoT) technology into solar photovoltaic (PV) systems offers significant advantages, notably in real-time remote monitoring, low-power IoT implementation, and adaptive Maximum Power Point Tracking (MPPT) performance. Real-time monitoring facilitates continuous tracking of system performance metrics, enabling proactive maintenance and swift responses to operational anomalies. The use of the ESP8266 module ensures that IoT capabilities do not significantly impact overall energy consumption, preserving the efficiency gains achieved through advanced MPPT control. Additionally, the fuzzy logic-based MPPT controller enhances the system's adaptability to varying environmental conditions, particularly partial shading, thereby maximizing energy harvest.However, the incorporation of advanced control algorithms and IoT components results in a slightly higher initial cost compared to traditional PV systems. For instance, the cost of IoT hardware and sensors can range from $500 to $2,000 for a small-scale home IoT solar project with a 5kW capacity. To address this concern, future work will focus on exploring the use of PCB-integrated flexible sensor arrays. This approach aims to reduce material and assembly costs while maintaining or improving sensor performance and system reliability. Additionally, implementing preventive maintenance strategies, including regular performance monitoring and system diagnostics, can help identify potential issues before they become major problems, reducing the need for costly repairs.

CONCLUSION

The integration of adaptive fuzzy logic MPPT algorithms and IoT technology significantly enhances the efficiency and reliability of solar PV systems, particularly in regions with challenging microclimatic conditions. The system's real-time monitoring and remote diagnostics capabilities make it a promising solution for off-grid and rural electrification applications. The fuzzy logic-based MPPT controller proved to be more responsive and stable than traditional methods, optimizing energy harvest under dynamic conditions. While the initial costs are higher due to the inclusion of IoT components and advanced control algorithms, the long-term benefits in terms of energy yield, system reliability, and maintenance efficiency justify the investment. Future work will focus on reducing the cost of IoT hardware through PCB-integrated flexible sensor arrays and exploring preventive maintenance strategies to further enhance system performance and reduce repair costs.

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CITE AS: Mwebe Robert and Twesimme Mirembe (2025). Optimization in Varying Microclimates. Design and Fabrication of an IoT-Integrated Smart Solar PV Module with Adaptive MPPT for Real-Time Performance. IDOSR JOURNAL OF COMPUTER AND APPLIED SCIENCES 10(1):6-16. https://doi.org/10.59298/JCAS/2024/101.6160